Use of Radio Frequency Identification (RFID) Tags in Hot Mix Asphalt

Phase I Technical Report

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USE OF RADIO FREQUENCY IDENTIFICATION (RFID) TAGS IN HOT MIX ASPHALT

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

USE OF RADIO FREQUENCY IDENTIFICATION (RFID) TAGS IN HOT MIX ASPHALT

INTRODUCTION

In order to ensure—and ideally to improve—the performance of asphalt pavements, it is vital that the influence of material properties on performance be clearly understood. Correlations between as-constructed properties of asphalt concrete in construction databases and field performance of pavements in pavement management systems can quantify the link between material quality and performance.

Unfortunately, the dissimilar ways in which these two sets of data are recorded with respect to location along the pavement alignment makes it difficult to establish these correlations. Hot mix asphalt (HMA) concrete is produced at a production facility and then trucked to the highway construction site for offloading into the asphalt paver. HMA producers sample their production periodically and perform various quality control (QC) tests to ensure that the mixture properties (gradation, volumetrics) remain within acceptable limits. Agencies typically take additional samples for quality acceptance (QA) testing to corroborate the producer's QC test results and to establish pay factors. QC and QA samples are typically taken at specified tonnage intervals from delivery trucks as they leave the asphalt plant. For example, in Maryland, a minimum of one QC sample (volume sufficient for the full suite of tests) is typically taken for each 1000 tons of production. This corresponds roughly to one truck out of every 50 leaving the plant. Tests results from this sample are assumed to be representative of the entire 1000 tons of production. In Maryland, one QA sample is also taken for each day's production (on the order of 4000 tons or more). Additional in-place material property tests (cores, nuclear density) are also typically performed on the compacted mat.

For a 2 inch overlay, 1000 tons of production corresponds to approximately 1.25 lane-miles of paving. Unfortunately, at present there is no good practical way to record precisely where within this length of paving the sampled truckload is deposited. In many instances, the milepoint range for the entire 1000 tons of production represented by the sampled truckload is not even recorded. This becomes a serious problem later when attempting to correlate as-constructed material properties with measured performance from a pavement management system, since pavement management data is typically referenced to a specific spatial location on the roadway (milepoint, latitude/longitude). Unless the HMA QC/QA data can also be tied to a spatial location along the pavement, it cannot be correlated accurately with pavement management data.

The concept explored in this project is the development and testing of an inexpensive expendable electronic sensor based on radio frequency identification (RFID) technology that can be used to identify or tag truckloads of hot mix asphalt as they leave the production plant. This sensor would pass through the paver and be compacted into the finished mat. After construction, a vehicle-mounted scanner would be used to electronically "read" the identity tags and cross-reference them with GPS latitude and longitude coordinates. These data could then be directly linked to as-constructed in-place test results and to future pavement performance data recorded in the agency's pavement management system, enabling robust statistical analyses of the correlations between material properties and actual performance.

PHASE I RESULTS

Task Order 1 of the contract corresponds to the Phase I work plan from the original proposal. The Phase I effort, the subject of this report, has focused on the development and evaluation under laboratory conditions of prototype RFID devices that can survive the harsh application of HMA production and paving. A plan for field evaluation of the devices under real-world asphalt production and paving conditions during the subsequent Phase II has also been developed. The period of performance for Phase I was 18 September 2006 through 17 June 2007.

The Phase I work plan is divided into two tasks:

Phase I: Feasibility/Concept Development

Task 1: Identify Feasible RFID Devices for HMA

Task 2: Identify Candidate Field Projects

Each of the Phase I tasks is detailed in the following subsections. The field evaluation plan will be executed in Phase II after approval and notice to proceed from FHWA.

Task 1: Identify Feasible RFID Devices for HMA

The task is organized into three work elements: (1) literature review; (2) identification of appropriate RFID technology; and (3) prototype tag development.

Work Element 1.1: Literature Review

The literature review was completed during Phase I. This review focused on the areas of RFID technology and applications in the general areas of civil engineering and construction. Specific RFID applications identified in these areas include the following:

- Tracking of PCC test specimens
- Maturity monitoring of in-place PCC
- Tracking of construction materials at project site (e.g., fabricated pipe)
- Construction tool inventory/usage control/monitoring
- Location identification of buried infrastructure (cables and pipes)

An annotated bibliography of the articles reviewed as part of this work element are include as Appendix A of this report. The key facts and findings from the reviewed literature provided guidance for the efforts under Work Element 1.2 as describe in the following subsection.

In conjunction with the literature review, the Principal Investigator attended the “Research Opportunities in Radio Frequency Identification (RFID) Transportation Applications Conference” organized by the Transportation Research Board and held at the National Academies Keck Center on October 17-18, 2006. This conference was enormously helpful, both in providing basic background information on RFID applications in related areas but also in meeting some of the key civil engineering researchers currently active in this field.

Work Element 1.2: Identification of Appropriate RFID Technology

Aspects of RFID technology of relevance to this project include the following:

- Physical size of the tag
- Operating frequency (low, high, ultra-high, and microwave; this influences tag size and readout range)
- Type of tag (active or passive; this influences cost, power consumption, and maximum readout range)
- Read range (including high-gain antenna design)
- Durability/survivability (e.g., strength of tag encapsulation; maximum/operating temperature ranges)
- Cost of the expendable tag

Some light was shed on these aspects by articles from the literature review. However, other lines of inquiry were also pursued: (1) consultations with Dr. Marc Cohen, a research scientist the Center for Engineering Logistics and Distribution in the University's Institute for Systems Research; and (2) exploratory laboratory studies.

Dr. Cohen has extensive experience in RFID technology. Discussions with him confirmed and expanded the conclusions reached from the literature review (see also Table 1):

1. For a physical tag size on the order of 1 inch, the UHF frequency range is optimal.

2. Passive tags, which are preferred because of their cost differential relative to active tags, should be able to provide the requisite read range performance.

3. Commercially available RFID readers are readily available for vehicle mounting (e.g., antennas on a front bumper) with read ranges on the order of 1 meter or more, sufficient for our applications.

4. Possible attenuation of the RFID signal by the asphalt concrete could be an issue and therefore needed to be explored early.

5. Although thermal and mechanical survivability will be key challenges. The maximum temperature range tolerable for short periods (e.g., the time required to truck a load of asphalt from the production plant to the paver) is significantly higher than typical rated operating and/or storage temperatures for RFID tags.

Table 1. Characteristics of different RFID technologies.

Type	**Frequency**	**Pros/Cons**	**Read Range (ft)**	
			Passive	**Active**
LF	125 KHz	Require less power, better penetration of non-metallic and/or high water content substances	1	
HF	13.56 MHz	Work well on metal objects	3	
UHF	860-960 MHz	Better range, faster data transfer. Use more power. More “directed,” require a clear path between tag and reader. Largest application area, widest installed base in industry.	10-20	100-300
MW	2.45 GHz			

Preliminary Evaluations

Potential attenuation of the RFID signal by the asphalt surrounding the embedded tag could have a major impact on read range and thus system practicality. Since this aspect is vital to the project, it was evaluated early on in a very preliminary way as part of the identification of appropriate RFID technologies in this work element. Jaselskis *et al.* (2003) describe the theoretical aspects of electromagnetic wave interaction with materials, with a particular focus on asphalt concrete. The key material property governing the transmission of dielectric materials is the permittivity. A dielectric material is an electrical insulator. A vacuum is the ideal insulator, but many materials—e.g., asphalt concrete—also fall into this category. When an electric field interacts with a dielectric medium, redistribution of charges within its atoms or molecules alters the shape of the field both inside and around the medium. The *absolute permittivity*, ε_a, is the fundamental physical quantity governing the interaction between and electric field and a dielectric medium. It is a measure of the ability of the medium to polarize and thus reduce the strength of the field. In other words, permittivity defines a materials ability to transmit or “permit” an electric field. The relative permittivity or *dielectric constant*, ε, is the permittivity of a material relative to that of an ideal vacuum, ε_0:

$$\varepsilon = \frac{\varepsilon_a}{\varepsilon_0} \tag{1}$$

According to Maxwell’s equations for non-magnetic media, for an electric field **E** induced by the incident electromagnetic wave:

$$\mathbf{E} = \mathbf{E_0} e^{i\omega t} \tag{2}$$

the displacement vector **D** is expressed as:

$$\mathbf{D} = \varepsilon_0 \varepsilon(\omega)\mathbf{E} \tag{3}$$

in which:

ω = circular frequency of the wave
ε_0 = permittivity of vacuum = 8.85x10^{-12} Farads per meter (F/m)

$\varepsilon(\omega)$ = frequency dependent relative permittivity (dielectric constant) of the medium
= $\varepsilon_a(\omega)/\varepsilon_0$, where $\varepsilon_a(\omega)$ = absolute permittivity
i = $\sqrt{-1}$

The displacement field **D** represents how the electric field **E** influences the organization of electrical charges in a given medium. The total current flowing within a medium is divided into conduction and displacement components. The displacement current can be thought of as the elastic response of the material to the applied electric field. As the magnitude of the applied field is increased, an increasing amount of energy is stored in the displacement field. If the electric field is subsequently decreased, the material will release the stored energy.

Due to inertia processes in fluctuating electromagnetic fields, the displacement field **D** for most materials is not in phase with the electric field **E**. As a consequence, the relative permittivity is a complex frequency-dependent quantity $\varepsilon(\omega)$:

$$\varepsilon^*(\omega) = \varepsilon'(\omega) - i\varepsilon''(\omega) \tag{4}$$

The real part of the permittivity, $\varepsilon'(\omega)$, is a measure of polarization and is thus a measure of the energy stored in the medium while the imaginary part, $\varepsilon''(\omega)$, defines the average power absorbed and/or scattered by the medium and thus is a measure of energy loss. This energy loss can also be related to the electrical conductivity σ for the given frequency:

$$\varepsilon''(\omega) = \frac{\sigma}{\varepsilon_0 \omega} \tag{5}$$

The net effect of all of the above is that electromagnetic wave propagation is impeded as the permittivity increases. Maximum RFID read range will when the RFID electromagnetic waves travel through a material with a low dielectric.

For asphalt concrete, both the real and imaginary permittivity components will be functions of the mixture composition, moisture content, and density. Jaselskis *et al*. (2003) measured the complex relative permittivity components as a function of frequency for several asphalt concrete mixtures. Typical results for the real and imaginary permittivity components are shown in Figure 1 and Figure 3 for a typical asphalt mixture consisting of a sand aggregate having 8.4% binder by weight and compacted to three different density levels. For RFID UHF frequencies on the order of 1000 MHz, the real component of the relative permittivity varies between about 4.5 and 5.5 (dimensionless) while the imaginary (loss) component ranges is approximately 0.2 to 0.3—i.e., a small value. Figure 3 summarizes the temperature dependence of the permittivity components for this same mixture, but at a frequency of 1 MHz. For hot mix asphalt construction, the temperature range of interest is from approximately room temperature (20^{o}C or 290 K) up to the mixing and compaction temperature (maximum of about 170^{o}C or 440 K)—i.e., the entire temperature range shown in the figure.

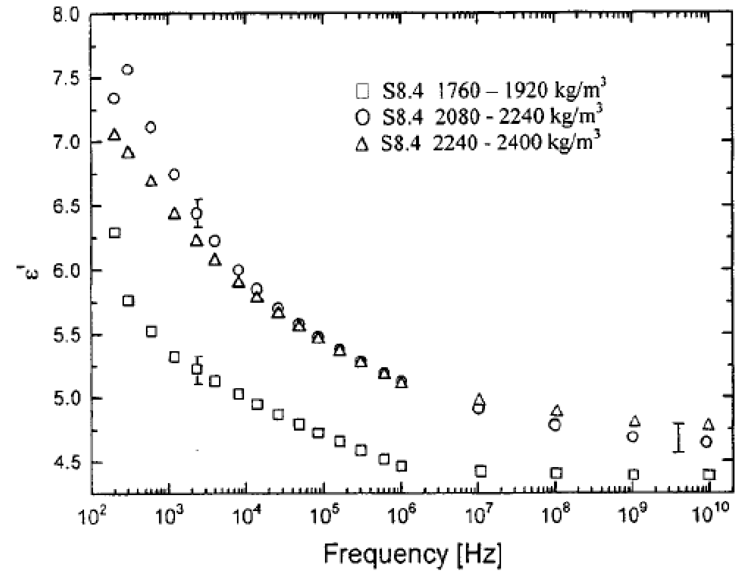

Figure 1. Frequency dependence of permittivity for a typical asphalt mixture at room temperature (Jaselskis et al., 2003)

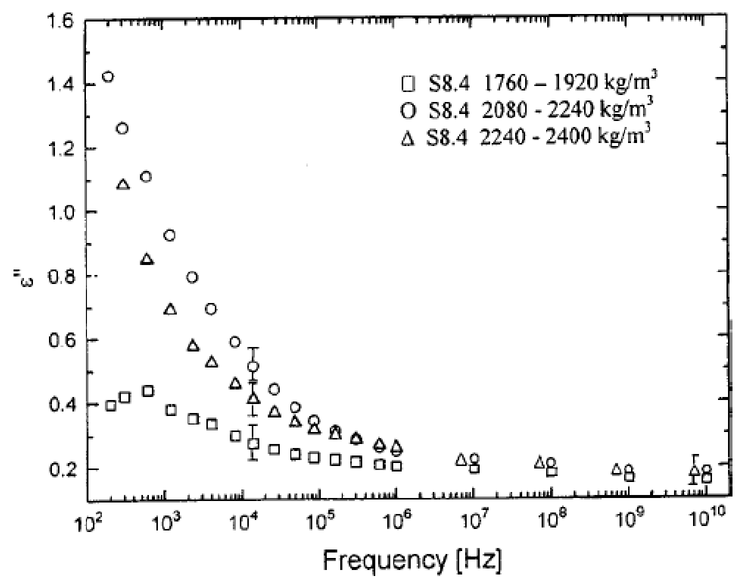

Figure 2. Frequency dependence of loss for a typical asphalt mixture at room temperature (Jaselskis et al., 2003).

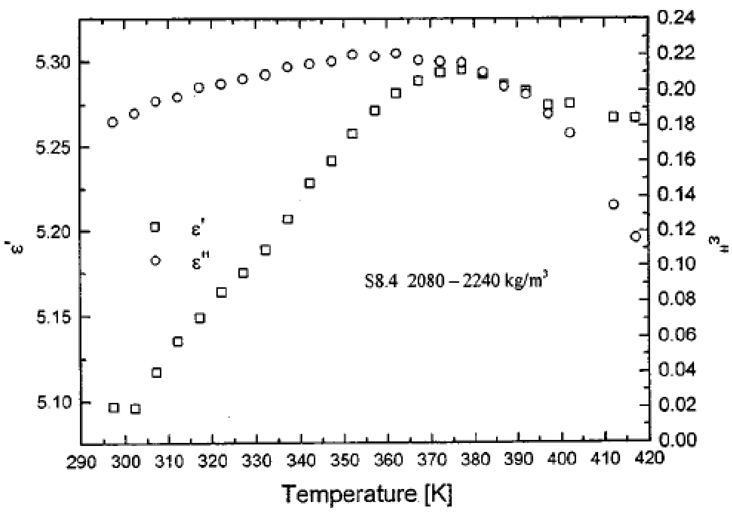

Figure 3. Temperature dependence of real and imaginary permittivity components for a typical asphalt mixture at 1 MHz (Jaselskis et al., 2003).

The theoretical description of electromagnetic wave propagation and losses in terms of relative permittivity is placed in better context through comparisons with other materials. Table 2 summarizes relative permittivity values for construction and related materials. Asphalt concrete typically has a relative permittivity of between 3.5 and 5.0, comparable to Portland cement concrete, aggregates, and other similar materials. This range lies closer to the properties of good UHF media—e.g., vacuum, air—and relatively far away from poor UHF media—e.g., water—suggesting that attenuation losses of RFID signals through asphalt concrete should be modest.

Table 2. Typical dielectric constant (relative permittivity) values for common materials.

Material	**Dielectric Constant**	**Frequency Range**
Vacuum	1.0	
Air	1.00054	
Teflon (polytetrafluorethelene)	2.0 to 2.1	
Polyethylene	2.25	
Bitumen	***2.38***	
Polystyrene	2.4 to 2.7	
Polyvinylchloride	3.3 to 4.55	
Porous asphalt concrete	***3.6 to 4.1***	***50 MHz to 1.6 GHz***
Dense graded asphalt concrete	***4.4 to 5.0***	***50 MHz to 1.6 GHz***
Concrete	4.5	
Quartzite aggregate	4.95	
Granite	6.25 to 5.75	60 MHz to 1.4 GHz
Glass	6.775	
Rubber	7	
Silicon	11.68	
Cement mortar	20 to 30	1 MHz to 300 MHz
Water	80	

As a complement to this theoretical assessment of RFID signal attenuation in asphalt concrete, a companion exploratory laboratory study was undertaken. The attenuation of UHF RFID signals through asphalt were evaluated via the inexpensive RadarGolf system (http://www.radargolf.com/), a golf ball locating aid based on technology that is similar but not identical to RFID. The RadarGolf system consists of a hand-held reader and standard golf balls with an embedded chip and antenna located just below the surface covering (Figure 4). The hand-held reader transmits at 914 MHz, and the instrumented ball responds at 1828 MHz. Unlike true RFID, the return signal does not include a unique digital signature for each golf ball. Nonetheless, given the low cost ($200) of the system and its operation in the same UHF frequency range (for transmission) contemplated for the RFID application in this project, it seemed a suitable vehicle for some simple exploratory tests of signal attenuation in the laboratory.

Figure 4. RadarGolf reader (signal strength bars shown as concentric arcs on left—from www.RadarGolf.com).

Figure 5. RadarGolf ball design (www.RadarGolf.com).

Figure 6 summarizes the measured signal strength vs. distance relationship for RadarGolf balls in air. All trials were conducted in the parking lot outside the Civil Engineering laboratory building. Signal strength is indicated on the RadarGolf reader by a series of bars similar to cell phones, with 10 bars representing maximum strength. Each data point in Figure 6 represents the average of three trrals. The maximum measured read range for the RadarGolf balls in air averaged 112 feet.

In order to investigate potential signal attenuation due to embedment in asphalt concrete, RadarGolf balls were inserted in various sizes of cored Superpave gyratory compactor specimens that were shielded with aluminum foil around the curved sides to avoid spurious signals (see Figure 7). The RadarGolf ball was then read in the axial direction in the laboratory. It was found that up to 5 inches of asphalt had negligible influence of signal strength and that full signal strength (10 bars) could be achieved at a read range of up to 7.5 feet. In one trial the upper gyratory plug was saturated to simulate a wet pavement; this had no effect on the measured read range.

As a final evaluation, one RadarGolf ball was compacted in a cold mix asphalt specimen using a Superpave gyratory compactor. The specimen was compacted to approximately 4% air voids after 225 gyrations. The maximum read range after compaction was 18 feet. All of these conclusions suggested that UHF RFID signal attenuation by asphalt concrete should not be a serious issue.

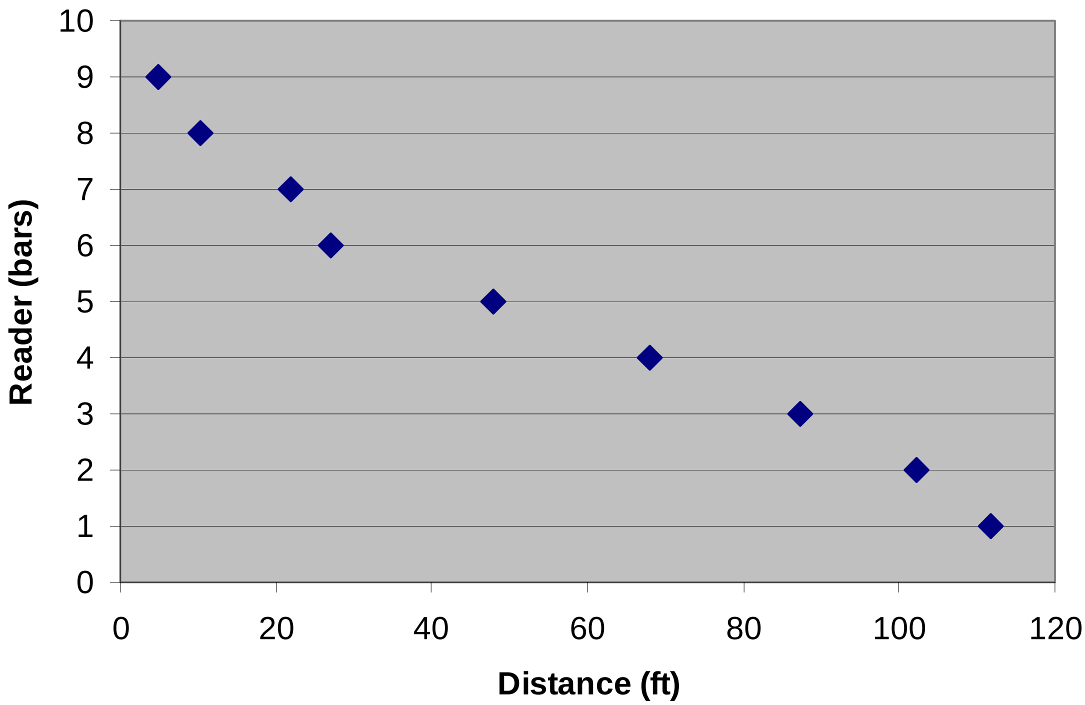

Figure 6. RadarGolf signal strength vs. distance in air.

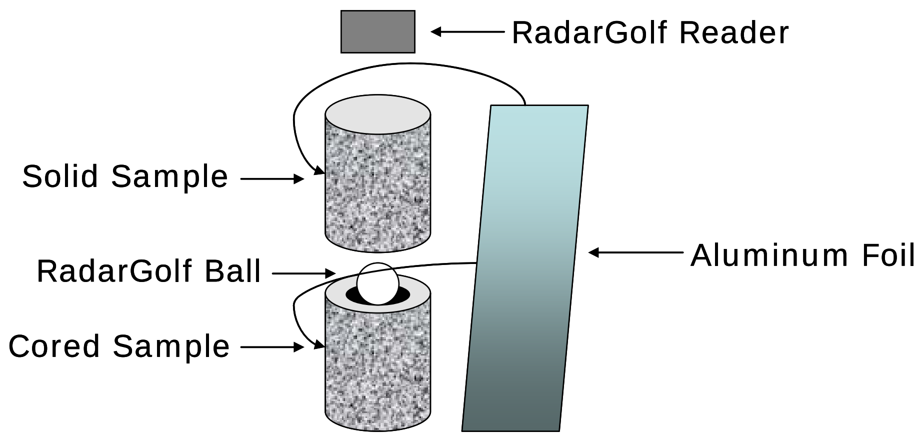

***Figure 7*. Experiment for evaluating RFID signal attenuation through asphalt using RadarGolf system.**

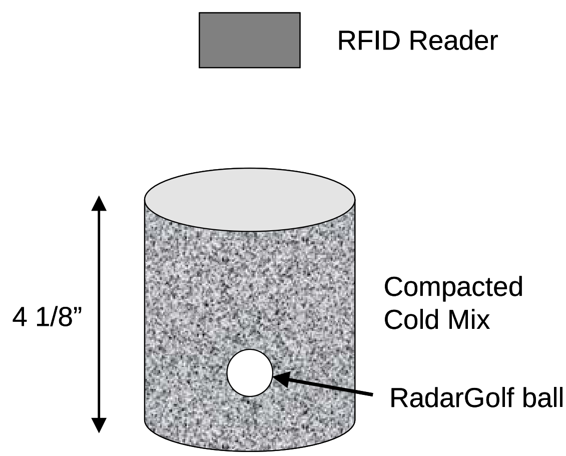

Figure 8. RadarGolf ball compacted in a gyratory plug of cold mix asphalt.

Industrial-Grade RFID System

The literature review, theoretical evaluations, and exploratory work with the RadarGolf system provided sufficient background and confidence to purchase an industrial-grade RFID system. Based on a careful review of the specifications and available product reviews for various manufacturers' systems, the Mercury 5 RFID reader from ThingMagic was selected as most suitable for this project. Key specifications of the Mercury 5 reader include:

Hardware

- Name: ThingMagic Mercury 5
- Processors: Intel IXP4xx Network Processor
  Texas Instruments Digital Signal Processor

- Memory: 64 MBytes DRAM
  16 MBytes FLASH
- Connectivity: RS-232 serial interface
  10/100 Base-T Ethernet interface

Mechanical and Environmental

- Dimensions: 25.4 x 25.4 x 3.8 cm
- Temperature: 0^oC - 40^oC operating
  -20^oC – 70^oC storage
- Humidity: 0 – 90% relative humidity (non-condensing)
- Weight: 3 lb 10 oz / 1.6 kilograms
- Power: 24V DC 2A unregulated

Radio Frequency

- Operating Frequencies: 902-928 MHz
- Air Interface Protocols: EPC Class 0
  EPC Class 1
  EPC Generation 2
  ISO 18000-6B / Unicode 1.19
  Rewritable Class 0+
- RF Power: +32.5 dBm (1 Watt (30 dBm) per FCC Part 1.5;
  +2.5 dB attenuation due to antenna cables)

The ThingMagic Mercury 5 was purchased as a complete start-up system including the reader, two bistatic circular antennas, four 25 ft. cables, a startup CD, and a selection of RFID tags (Figure 9).

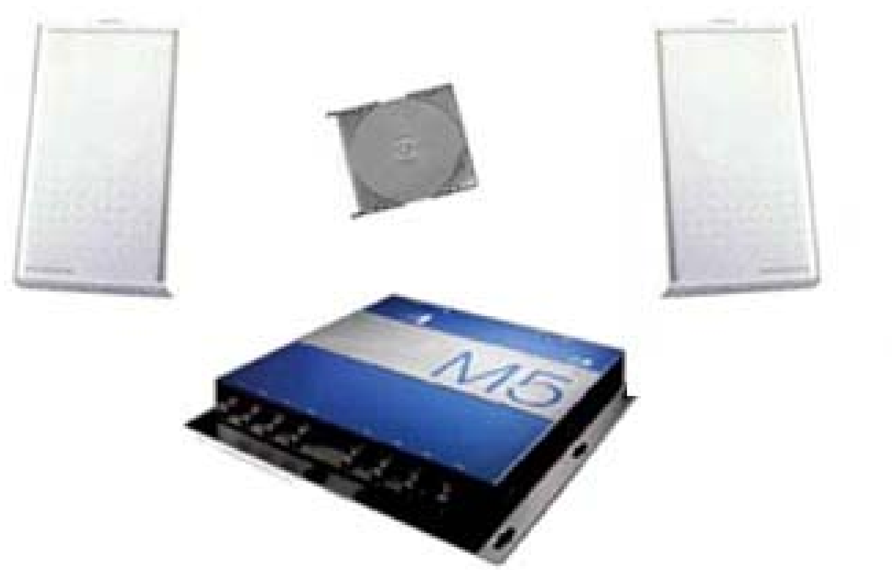

Figure 9. ThingMagic Mercury 5 start-up kit.

Suitable tags compatible with the Mercury 5 reader and meeting size limits were also identified. Key features of these tags are summarized in Table 3. Sample quantities were obtained for the Alien Gen 2 1x1 and 2x2 tags (Figure 10). Attempts to purchase small trial quantities of the Avery-Dennison AD-812 tags were unsuccessful.

Table 3. Candidate RFID tags (all passive).

Vendor	**Model**	**Freq (MHz)**	**Size (mm)**	**Temperature Range (^oC)**		**Comments**
				Operating	**Storage**	
Alien	Gen 2 1x1	902-928	25.4 x 25.4	-25 to +65		Small form factor optimized for plastic packaging such as pill bottles; nominal read range of 1.25 – 2.5 meters.
Alien	Gen 2 Mini-Squiggle	902-928	27 x 10	-25 to +65		Nominal read range of 1 – 1.5 meters.
Alien	Gen 2 2x2	860-960	47 x 42	-25 to +65		Omni-directional
Avery-Dennison	AD-812	902-928	25.4 x 25.4	-40 to +65	-40 to +85	Designed for superior edge-on read performance.

(a) 1 x 1 tag

(b) 2x2 tag

Figure 10. Alien RFID tags selected for evaluation.

Linking of the RFID tag identifier with GPS latitude and longitude coordinates is also an important technological component of this project. A Garmin GPS 12 transponder was borrowed from the Civil and Environmental Engineering department for preliminary evaluation of the best methods for linking GPS with RFID. The preliminary findings suggested that a data logger would be an easier technology for linking the RFID tag data to latitude and longitude coordinates. A GPS data logger records a constant stream of latitude/longitude/time values which can then be matched *post facto* to the time stamps on the RFID tag data. An inexpensive Pocket Tracker Pro system from Brickhouse Security (www.brickhousesecurity.com) was therefore acquired for use on the project. Key features of the Pocket Tracker Pro system useful for this project include: (a) location accuracy to within 2.5 meters; (b) read rate of one location point per second; (c) magnetic vehicle mount; (d) USB computer interface; (e) 100 hour battery life (AAA batteries); and (f) low cost.

Figure 11. Pocket Tracker Pro GPS data logger.

Work Element 1.3: Prototype Tag Development

Fabrication

Encapsulation of the RFID tags to protect them from temperature extremes and compaction stresses is key to their use in asphalt paving applications. Two candidate encapsulation media were considered: ceramics and high-temperature epoxy. Upon evaluation of these two materials, the ceramics were discarded because of high cost and fabrication difficulties. A high temperature epoxy, Durapot™ 866 from Contronics, Inc. (www.contronics.com), was selected as a suitable encapsulating material. Durapot™ 866 is a thermally and electrically insulating compound that forms a low density non porous foam for high temperature applications. This two-part epoxy, after proper curing at room temperature for 24 hours followed by oven curing at 120°C for 4 hours, has an upper temperature limit of 500°F, more than adequate for asphalt applications.

Suitable molds for encapsulating the RFID tags in the high temperature epoxy are also required. Various types of cookie and other kitchen molds were tried for the Alien 1x1 tags. For the Alien 2x2 tags, a different approach was adopted initially in which the tags are curled and then placed inside a 2 inch length of ¾ inch internal diameter steel pipe, after which the pipe is filled with high temperature epoxy. Various types of backing material evaluated for adding strength to the 2x2 RFID tags before curling and casting included 1/32 inch thick polytetrafluoroethylene (Teflon™) sheets, a 23/64" by 23x64" neoprene rubber mesh, and a 0.512" by 0.233" polytetrafluoroethylene diamond mesh. Backing material samples were obtained from McMaster-Carr Supply Co. (www.mcmaster.com).

Removal of the hardened epoxy from the molds was expedited by Ease Release™ 200, a general purpose release agent for molds and castings available from Smooth-On, Inc. (www.smoothonsecure.com/store/). Ease Release™ 200 is effective on polyurethane elastomers, epoxy resin, polyester resins, RTV silicones, rubber, and thermoplastic polymers and on aluminum, chrome, RTV silicone, epoxy, rubber, and steel molds. Even with the release agent, however, it was often difficult extruding the curled 2x2 tags from the steel pipe molds.

Because of the difficulty in extruding the 2x2 tags from the steel pipe molds, an alternative casting scheme using chlorinated polyvinylchloride (CPVC) pipe was also evaluated. CPVC is a thermoplastic commonly used for cold and hot piping systems in building construction. It has a glass transition temperature of approximately 110^{o}C and a melting point of 212^{o}C, which is sufficient for use with hot mix asphalt. The 2x2 tags were curled inside two inch long sections of 5/8 inch internal diameter CPVC pipe. This inside diameter was just sufficient that the ends of the curled tags did not overlap. Curling the tag with the antenna facing outward or inward had no influence on the read range. The pipe with tag was then filled with the high temperature epoxy and cured. Because the CPVC pipe is transparent to the RFID signal and has a melting point higher than the HMA compaction temperature, there was no need to extrude the tag after curing of the epoxy.

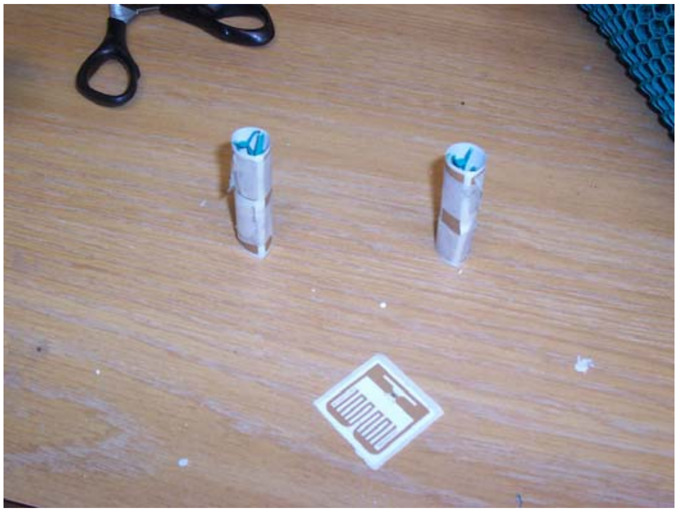

Figure 12. Alien Gen 2 2x2 tags after rolling and before insertion into ¾" diameter pipe.

Figure 13. Tags after encapsulation. A curled 2x2 tag after extrusion from pipe is shown on left. Remaining three tags are flat 1x1 tags.

Baseline Read Ranges

The maximum read range in air was measured using the Mercury 5 reader. Initial testing was performed by holding the tags by hand at various distances from the reader antenna until a signal could no longer be obtained reliably. The encapsulated 1x1 tags (rightmost tags in Figure 13) were readable at over 3 feet. This is only marginally acceptable for the intended application. The encapsulated 2x2 tags cast in and extruded from the steel pipe molds (leftmost tag in Figure 13) were readable to 25 ft, which is more than sufficient for the HMA paving application.

Once the general feasibility had been established via this initial testing, more precise evaluation of the read range was conducted near the end of Phase I. The focus of this evaluation was the curled 2x2 tags in the CPVC pipe sections because of their greater ease of fabrication. During this more precise evaluation it was discovered that there are several sources of interference that can alter the measured effective read range:

1. There appears to be a "body antenna" effect. Tags held by hand were discovered to have different read ranges than tags placed on an inanimate object with all persons removed to a distance. Even body movements 8 feet away from the tag would trigger a read when none had been observed before.

2. Placing the tags on the floor and then stepping some distance away gave more controlled conditions and consistent read data. The disadvantage of placing the tags on the floor and then reading them in a horizontal direction to determine maximum read distance is that the tags are slightly off the centerline of the antenna. This will tend to decrease the measured read range. The advantage, of course, is that placing everything on the laboratory floor is much easier than elevating everything several feet off the floor.

3. When a half-filled bucket of aggregate was accidentally placed behind one of the tags, the read range increased considerably. This may have beneficial implications for field vs. laboratory performance of the tags.

The read range tests were redesigned to minimize these compounding influences. The 1 ft x 2 ft RFID antenna was oriented perpendicular to the floor, supported along its long edge directly on the floor. A grid was laid out on the floor in front of the antenna. Tags were placed at each grid point and the observer stepped aside before tag read success was assessed. Replicate specimens and multiple reads were employed to improve the robustness of the test results.

The first series of tests employing this revised protocol were conducted on flat 2x2 tags before curling or encapsulation. Six read attempts were made at each grid point. Three of these were with the tag facing the antenna and three were with the tag facing away. The tag orientation was found to have no effect on the read success rate. Each grid point was assigned a value of 1 if the read success rate was greater than 50% for the six read attempts, a value of 0.5 if the tag could be read but the success rate was less than 50%, and a value of zero if the tag could not be read at all. A total of 6 tags were tested using this scheme. The results from this test series are summarized in Figure 14. Each block in the figure represents a 1 foot by 1 foot cell on the floor as viewed from above. The antenna is perpendicular to the floor (i.e., vertical), resting along its 2 foot long edge. Note that the antenna assembly contains separate transmit and read antennas along its length, as indicated by the "T" and "R" designations in the figure. The numeric values in Figure 14 represent the total score in each cell for the six tags and the color coding depicts the read success rate category (all tags read, >50% tags read, <50% tags read, zero tags read). Overall, the results in Figure 14 suggest an effective read range of about 7 feet for the flat 2x2 tags in air. There is some slight asymmetry in the read success pattern that may be due to experimental variability, local interference, and/or the asymmetric antenna design.

Antenna

	-4	-3	-2	-1	T	R	1	2	3	4
1		2	6	6	6	6	2			
2		5	6	6	6	6	6	1		
3			4	6	6	6	6	6		
4		2	6	6	6	6	6	6	5	
5			1	6	6	6	6	4	1	
6				5	6	6	6	5		
7			5	5	6	5	3			
8				3	1	2	2	2		

N=6

All tags read

>50% tags read

<50% tags read

No tags read

Figure 14. Read range for flat 2x2 tags in air. Tags oriented parallel to reader antenna. All distances in feet. T=transmit side of antenna, R=receive side.

The next series of tests was conducted on the curled 2x2 tags inside the CPVC pipe but before encapsulation in epoxy. This test series was designed to evaluate the effects of the curved tag geometry on read success. The pipes containing the curved tags were placed on the floor and parallel to the plane of the antenna in all tests. However, two orientations of the tags relative to the antenna were considered: the pipe axis horizontal with respect to the floor and parallel to the long axis of the antenna and the pipe axis vertical and parallel to the short axis of the antenna. The results from this test series are summarized in Figure 15 and Figure 16 for the horizontal and vertical orientations, respectively. It is clear from these figures that curling the tags does reduce the read range, and by a larger amount for the vertical orientation. Maximum effective read range in air in front of the antenna is approximately 5 feet for the horizontal orientation and 3 feet for the vertical, as compared to approximately 7 feet for the flat tag configuration.

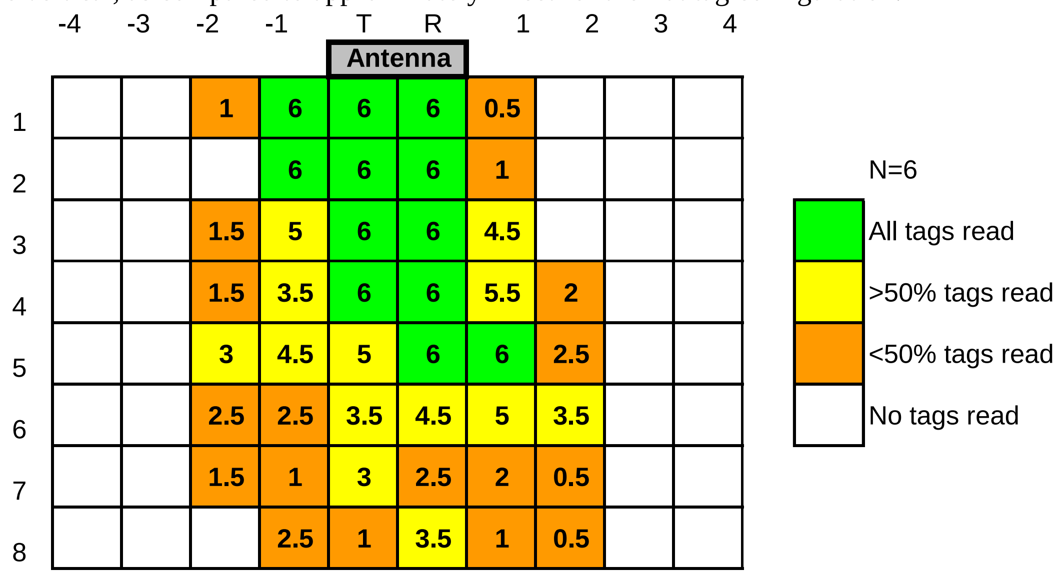

Figure 15. Read range for curled 2x2 tags in CPVC pipe before encapsulation and curing. Tags oriented in horizontal direction. All distances in feet. T=transmit side of antenna, R=receive side.

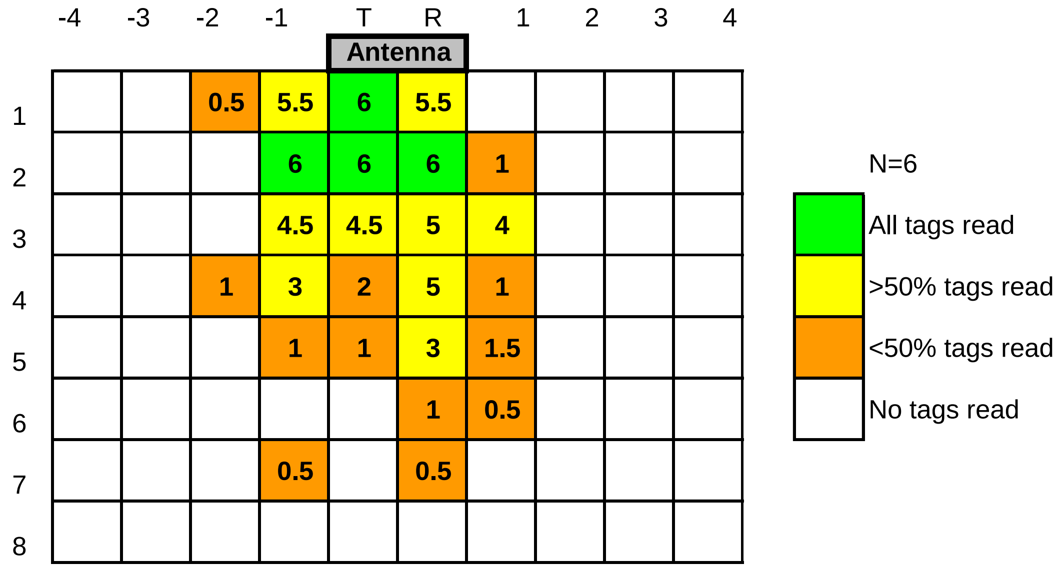

Figure 16. Read range for curled 2x2 tags in CPVC pipe before encapsulation and curing. Tags oriented in vertical direction. All distances in feet. T=transmit side of antenna, R=receive side.

Read ranges after encapsulation with epoxy and curing, the next stage in the fabrication process, are summarized in Figure 17 and Figure 18 for the horizontal and vertical tag orientations, respectively. Effective read range limits are reduced even further by the epoxy and curing process to approximately 2 feet for the horizontal orientation and 1 foot for the vertical. This may be because the 2x2 tags were curled with the antenna and chip facing inwards and the paper backing facing outwards. It is possible that there may have been some signal leakage from the antenna into the epoxy that is responsible for the reduced read range. Unfortunately, we were nearly out of tags and Phase I was drawing to an end when this phenomenon was discovered. It will have to be revisited at the beginning of Phase II.

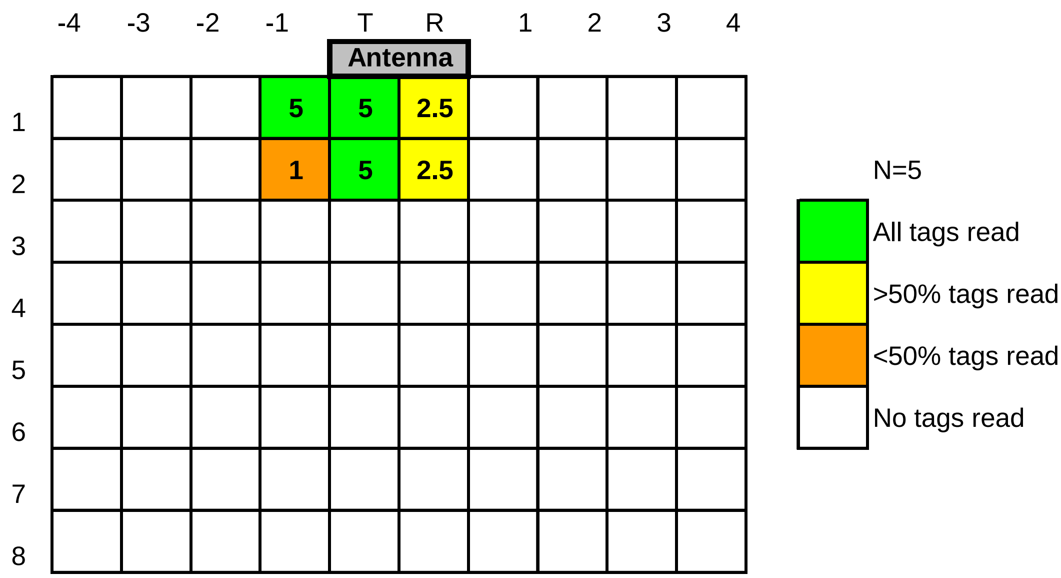

Figure 17. Read range for curled 2x2 tags in CPVC pipe after encapsulation and curing. Tags oriented in horizontal direction. All distances in feet. T=transmit side of antenna, R=receive side.

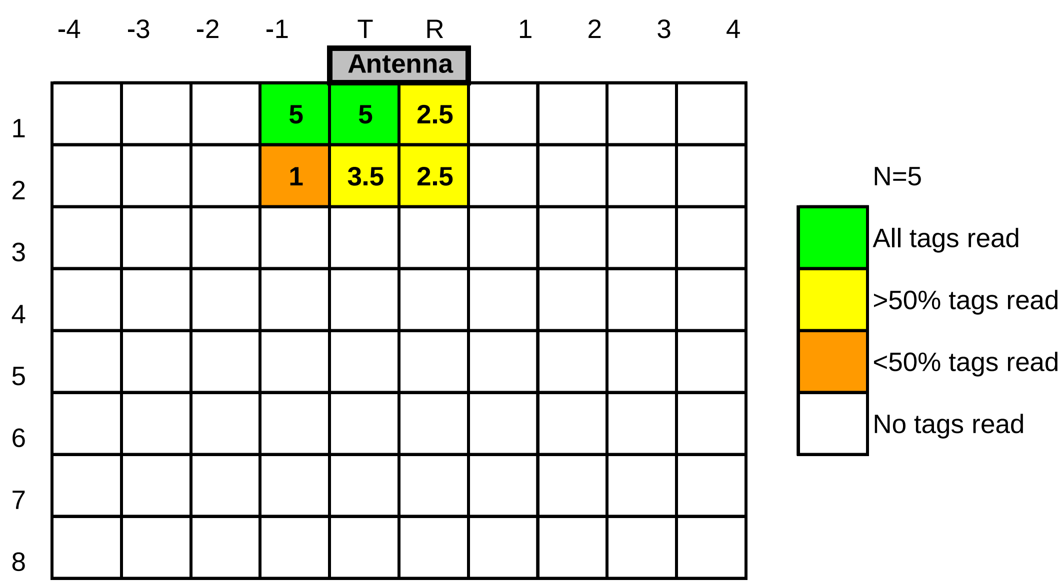

Figure 18. Read range for curled 2x2 tags in CPVC pipe after encapsulation and curing. Tags oriented in vertical direction. All distances in feet. T=transmit side of antenna, R=receive side.

Thermal Survivability

Thermal survivability is the first hurdle for the RFID tags, as typical mixing and compaction temperatures in HMA of up to 350^{o}F are well above their operating and long-term storage temperature limits. Thermal survivability was investigated in a preliminary way using the 1x1 encapsulated tags. As described previously, various backing materials had been acquired for trials to strengthen the tags during the encapsulation process. The combinations of backing materials and temperatures for the 1x1 tag tests are summarized in Table 4 below. Only one replicate was tested for each condition. All tags were left in the oven for 1.5 hours at the target temperature. The time duration was chosen to duplicate the longest time between placement of the tags in the truck load of hot mix at the plant to final cooling of the compacted mat in the field. Immediately after removal from the oven, none of the tags could be read. However, all tags read to a distance of 3 feet in air after being allowed to cool for 20 minutes. This is very similar to the baseline read for the 1x1 encapsulated tag prior to heating. The various backing materials appeared to have no influence on the final read range.

The preliminary investigation of thermal survivability was repeated with two encapsulated 2x2 tags. The first was heated for 1.5 hours at 300^{o}F; as with the 1x1 tags, the 2x2 tag could not be read immediately after removal from the oven but was readable up to a range of 10 feet after 20 minutes of cooling. The second 2x2 tag was heated to 350^{o}F and appeared to fail as it could not be read even after cooling. However, visual inspection suggested that the encapsulation may have been flawed, directly exposing part of the tag to the high temperatures.

Table 4. Conditions for thermal survivability evaluation of 1x1 tags.

Backing Material	Temperature
Teflon sheet	300^{o}F
Rubber mesh	350^{o}F
No backing	400^{o}F

Mechanical Survivability

Mechanical survivability was independently evaluated via gyratory compaction of the encapsulated tags into a cold mix asphalt product. Mechanical survivability was investigated in a preliminary way using the 1x1 encapsulated tags. The combinations of backing materials, gyrations, and maximum read range for the 1x1 tags are summarized in Table 5. Each tag was placed in the loose cold mix near the center of the mold and then compacted to various numbers of gyrations in the gyratory compactor. This is intended to simulate the stresses that the tags would feel during compaction in the mat in the field. All of the encapsulated tags survived the compaction. The maximum read range of 27 inches represents an approximately 30% decrease from the 3+ foot baseline read range prior to compaction. It is speculated that this reduction is due to the additional attenuation of the RFID signals through the asphalt rather than to any effect form the compaction itself. Figure 19 depicts the read testing of the tag after compaction.

The preliminary investigation of mechanical survivability was repeated with one encapsulated 2x2 tag compacted in the cold mix asphalt to 100 gyrations. Read range after compaction was approximately 10 feet. Again, this represents a decrease from the baseline read range through air of approximately 25 feet for the 2x2 tag.

One of the cold mix gyratory plugs was saturated in water after initial testing to evaluate the influence of pavement moisture on signal attenuation. No significant difference in read range was discerned between the dry and wet conditions.

Table 5. Conditions for mechanical survivability evaluation of 1x1 tags.

Backing Material	Number of Gyrations	Read Range (in.)
Teflon sheet	50	27.0
Rubber mesh	75	27.5
No backing	100	24.5

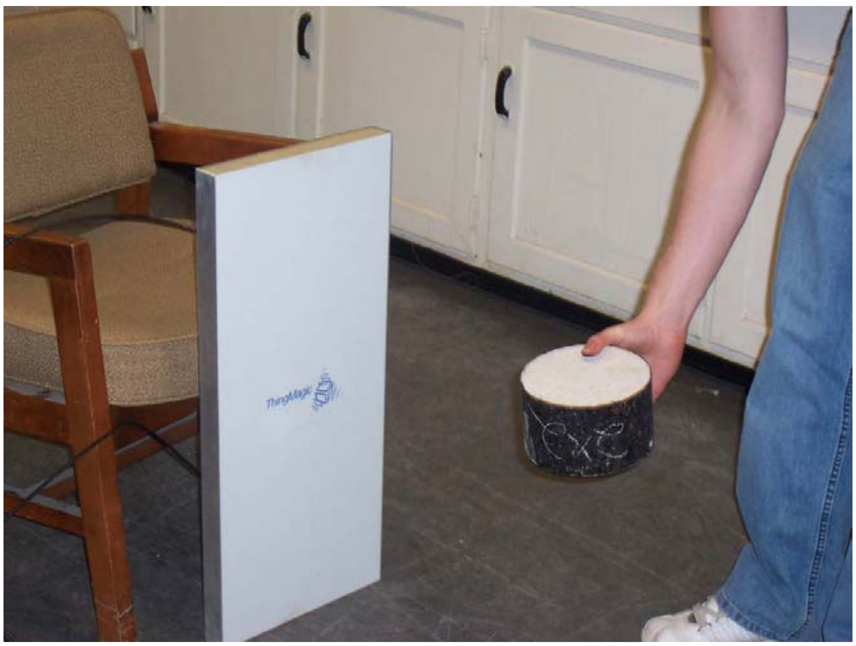

Figure 19. Read testing of tag compacted in cold mix asphalt.

Combined Thermal and Mechanical Survivability

Once the survivability of the tags under just thermal or mechanical torture had been established, the final test was survivability under combined conditions in the laboratory. This is intended to simulate the actual field scenario of transport of the tag in the truckload of hot mix asphalt followed by compaction into the mat behind the paver.

The hot mix asphalt used for this evaluation was a 19mm dense graded mix with a PG 64-22 unmodified binder. Tags were placed in an oven along with the loose mix for 1.5 hours at a temperature of 160°C before compaction. Two tags were placed in the loose mix in each gyratory mold near the axis at approximately the third points of the mold height. After compaction the gyratory plugs were extruded from the molds and then scanned in the axial direction by the RFID reader.

Figure 20 summarizes the read tests for one gyratory plug containing two tags that had been cast in and extruded from the steel pipe molds. Despite requiring significant hammering to extrude these two tags, both survived and were readable in the gyratory plug. During the read tests, the gyratory plug was rotated through 6 different positions (12:00, 2:00, 4:00, 6:00, 8:00, and 10:00). Each of the two tags was read in each position, yielding a maximum of 12 possible successful reads for the plug. No trends in read success or range could be observed between the closer vs. more distant tag. As shown in the figure, the maximum effective read range was only approximately 1 foot, which was substantially less than obtained in other trials of this tag type.

Figure 21 summarizes the read tests for three gyratory plugs each containing two tags that had been encapsulated in the CPVC pipe. For two of the plugs, only one of the two tags survived the heating and compaction. The six-position testing procedure was the same as described previously. Given that there were only four surviving tags among the three gyratory plugs, there was a maximum of 24 possible successful reads total. For the one plug in which both tags survived, there again were no trends in read success or range between the closer vs. more distant tag. As shown in the figure, the maximum effective read range was approximately 2 feet. This is roughly consistent with the effective read range for this tag type through air after encapsulation and curing (Figure 17 and Figure 18). In other words, the additional heating and compaction for the tags depicted by Figure 21 did not significantly degrade the effective read range.

Eight tags in all were oven heated and compacted into gyratory plugs. Of these, six survived and were able to transmit their identification numbers to the RFID reader when scanned. This corresponds to a survival rate of 75%. This is sufficient for field application, as it is envisioned that multiple tags will be tossed into the truckload of HMA for redundancy.

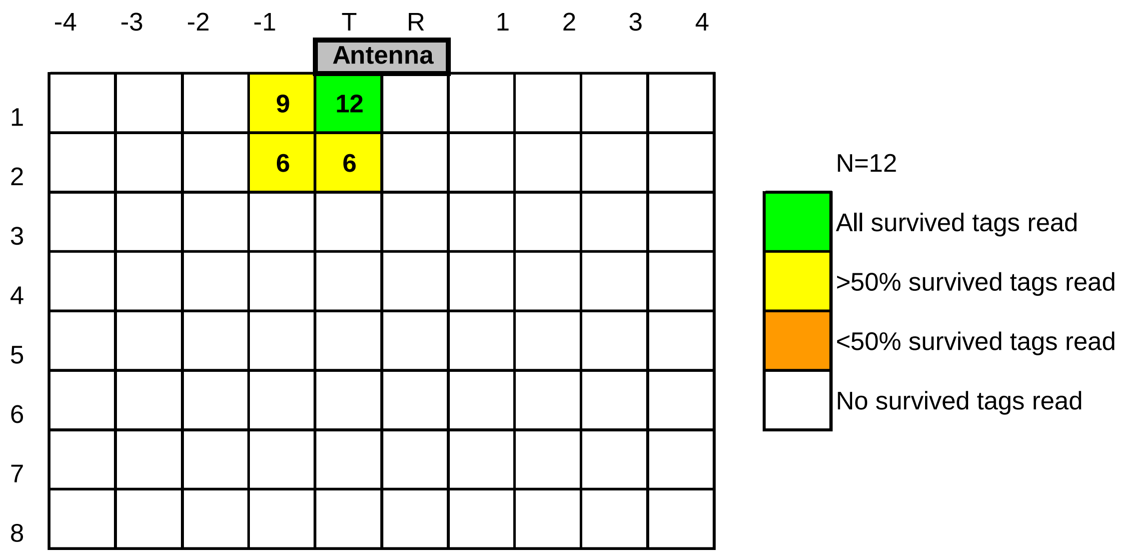

Figure 20. Read range for curled 2x2 tags cast/extruded from steel pipe mold after oven heating and gyratory compaction. All distances in feet. T=transmit side of antenna, R=receive side.

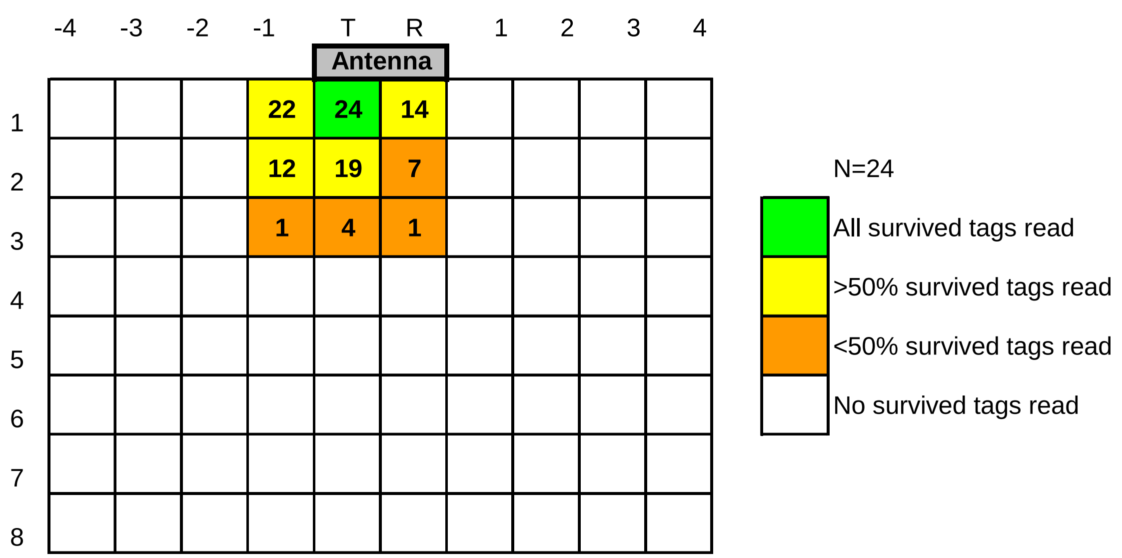

Figure 21. Read range for curled 2x2 tags in CPVC pipe after HMA oven heating and gyratory compaction. All distances in feet. T=transmit side of antenna, R=receive side.

Conclusions from Phase I Work Elements

The Phase I work under Task 1 identified UHF passive RFID technology as best suited to the hot mix asphalt paving application. Preliminary assessments concluded that attenuation of the RFID electromagnetic signals by the asphalt concrete should not be an issue. After considerable research of available products, appropriate RFID and related hardware was acquired for use in this project.

The Task 1 work also produced a feasible tag and encapsulation system that can survive the temperatures and compaction stresses inherent in HMA transport and paving. An Alien 2 inch by 2 inch RFID tag curled and encapsulated in high temperature epoxy inside a 5/8 CPVC or 3/4 inch steel pipe (tag extruded from steel pipe mold) provides a hardened tag of appropriate size. Read range appears to be adequate, although some of the data collected near the end of Task 1 showed the influence of potential interference and other factors on decreasing or increasing the maximum effective read distance. Nonetheless, the encapsulated tags appear sufficiently successful and robust to enable moving to Phase II field trials. It is expected that the tag encapsulation design and other details will be further refined during Phase II.

Task 2: Identify Candidate Field Projects

Field trials are to be performed in Phase II in cooperation with the Maryland State Highway Administration (MDSHA). The MDSHA agreed in the proposal for this project to make projects available for field evaluation. Impact of the field evaluation on production and paving is expected to be minimal. A few encapsulated RFID tags be thrown into the back of a QC sampled truck as it leaves the asphalt production plant. Observers from the project team will follow the truck as it leaves the plant and determine where the truck deposits its load into the paver to establish "ground truth." The tags in the truckload of HMA will then pass through the paver at the construction site and be compacted into the mat. The project team will read the tags electronically along with their corresponding GPS coordinates.

Ideally, four to six projects will be included in the field evaluation. The criteria for selecting these projects include:

1. A combination of overlay and new construction projects. New construction projects would ideally contain multiple HMA lifts. Rehabilitation projects would ideally include HMA overlays on both flexible and rigid pavements.

2. Different HMA mixtures—e.g., fine vs. coarse nominal maximum aggregate size (NMAS), stone matrix (SMA) vs. dense graded asphalt, etc.

3. Different HMA lift thicknesses, if possible.

4. At least one project where the project team can stay on the mat for some additional time after it cools to pursue more extensive field evaluation of the reader and field scanning protocols. This would most likely be a new construction project that has not yet been opened to traffic.

5. Geographical location not too distant from College Park.

6. Construction schedule compatible with the Phase II project schedule.

Potential MDSHA projects from the current construction season have been identified and discussed with Greg Moore, the MDSHA Asphalt Team Leader. The Wilson Bridge project has been identified as a good new construction project as it is not yet open to traffic and thus will meet criterion 4 above. Overlay paving projects on I95 and other Interstates will also be included. Mr. Moore indicated that many US, MD, and other highway paving projects in the College Park area are scheduled for this construction season, so identification of other field evaluation sites will largely hinge upon their dovetailing within the overall project schedule. MDSHA will coordinate with the asphalt producers and paving contractors on each project to smooth the way for the project team. Ms. Becky Smith and Ms. Gloria Burke will be the MDSHA personnel directly responsible for working with the project team during the field evaluation.

In summary, two specific projects have already been identified, and one of these is suitable for the more intensive field evaluations outlined in criterion 4. The other specific projects will be selected on the fly to satisfy schedule constraints once Phase II is underway.

The specific protocol for the Phase II field trials will consist of the following steps:

1. A research team member will be stationed at the asphalt plant to watch for trucks being sampled for QC purposes. Once a truck has been identified by plant personnel and sampled, the project team will throw 10 encapsulated tags into the load in the truck bed[1]. These tags will have been read previously to determine their unique identification codes. The sample IDs of the corresponding QC test specimens from the truck will also be recorded.

2. The research team member will follow the truck to the paving site and record where and when it deposits its load into the pavement. The times and milepoint locations of the start and end of paving operations with that load will be recorded. Paving operations will be closely observed for any hindrances or other problems caused by the tags in the load.

3. After the mat has been compacted and cooled sufficiently, the research team will perform the following tasks:

    (a) A walking visual inspection of the mat to look for exposed tags and/or any evidence of segregation or other defects around identified tags, etc. Photographic records will be taken as appropriate.

    (b) A portable reader apparatus will be wheeled onto the cooled mat to scan for tags. Upon reading a tag, the researchers will attempt to locate the tag in plan view as precisely as possible, either through read signal strength or visual observation. A GPS receiver will be used to record the latitude and longitude coordinates of all identified tags. The pavement area around each identified tag will be visually surveyed for any evidence of segregation or other defects.

    (c) Nuclear density readings will be taken over a grid surrounding the tag location to evaluate whether the tags are associated with any localized density anomalies.

4. After the mat has cooled completely but before opening to traffic, the research team will drive over the pavement with a truck mounted RFID reader and a GPS logger. The objective is to read the tags at speed and then link them to latitude and longitude position data. All data will be stored electronically for subsequent processing.

In addition to conventional laboratory notebook records (probably supplemented with recorded voice notes), digital photographs and videos will be taken as appropriate. The photos and videos

[1] Ten tags are likely far more than required for production paving operations. The large number of tags per truckload here will provide a factor of safety and a sufficiently large data set for developing survivability statistics.

will be useful for technology transfer purposes as well as providing additional recorded information.

Subsequent to paving and after all data have been collected, the RFID tag identification numbers will be linked to their corresponding in-place GPS latitude and longitude coordinates, which can then be linked to the appropriate production plan QC sample IDs for the lot/sublot. The MarylandWare QC/QA software already provides for storage of GPS coordinates for the QC/QA test samples. For demonstration purposes, the location-tagged QC/QA test data will then be linked with the corresponding pavement performance data from the MDSHA pavement management system (for overlay projects only).

Some ancillary studies are also contemplated during the Phase II field evaluation. Specifically, tests will be conducted to define the relationship between the speed of the vehicle containing the RFID reader and the read success rate. The ideal is a high read success rate while scanning the tags at traffic speed. The long term durability of the tags will also be evaluated in a very limited way within the short duration of Phase II. The read success rate will be determined at the very end of Phase II and compared against the corresponding rate immediately after construction.

PHASE II WORK PLAN

The Phase II work plan remains essentially the same as described in the original proposal. It will consist of two tasks:

Phase II: Field Evaluation
Task 3: Carry Out Phase I Plan
Task 4: Prepare Project Report and Technology Transfer

Each of these tasks will be briefly reviewed in the following subsections.

Task 3: Carry Out Phase I Plan

The encapsulated RFID tag designs developed in Task 1 of Phase I will be field tested to evaluate the following issues:

- Survivability under real world paving scenarios.
- Readout range under actual field conditions.
- Required redundancy (i.e., how many tags must be added to a truckload to locate the mix reliably along the pavement alignment; this is related to the survivability issue, but also includes delays in passing through the paver).
- Construction practicality issues—e.g., do the tags interfere with normal paving operations?
- Construction quality issues—e.g., doe the tags impair the quality of the compacted mat by inducing segregation or other defects?

As described under Task 2, all field trials will be thoroughly documented via notes, photographs, digital video, etc. to assist with subsequent technology transfer activities.

Some equipment fabrication will be required to carry out this task. Specifically, a portable hand-pushed RFID reader platform will be required for locating the precise location of the tags immediately after construction. A truck-mounted antenna bracket will also be required for higher speed scanning typical of production application.

The field evaluation will also include a demonstration of how the location-referenced test data from the RFID tagged material samples can be integrated into existing materials management and pavement management systems. UMD has worked with the MDSHA over the past several years on the customization of the MarylandWare software for collection and management of asphalt paving QC and QA data as well as on a prototype integrated materials management system. As shown in Figure 22, the MarylandWare software already includes provisions for tagging test data with latitude and longitude coordinates from hand-held GPS transponders. This software will be modified to include the identification code from the RFID tags read in the field trials. An example of how this location-referenced information can be merged with existing performance data in the MDSHA PMS will also be developed. This example, which will be developed for a field trial involving the overlay of an existing pavement, will be somewhat artificial because no performance data will yet be available from the PMS for the new overlay. However, the location-referenced material property data can be merged with the performance data for the underlying pavement as a demonstration of concept.

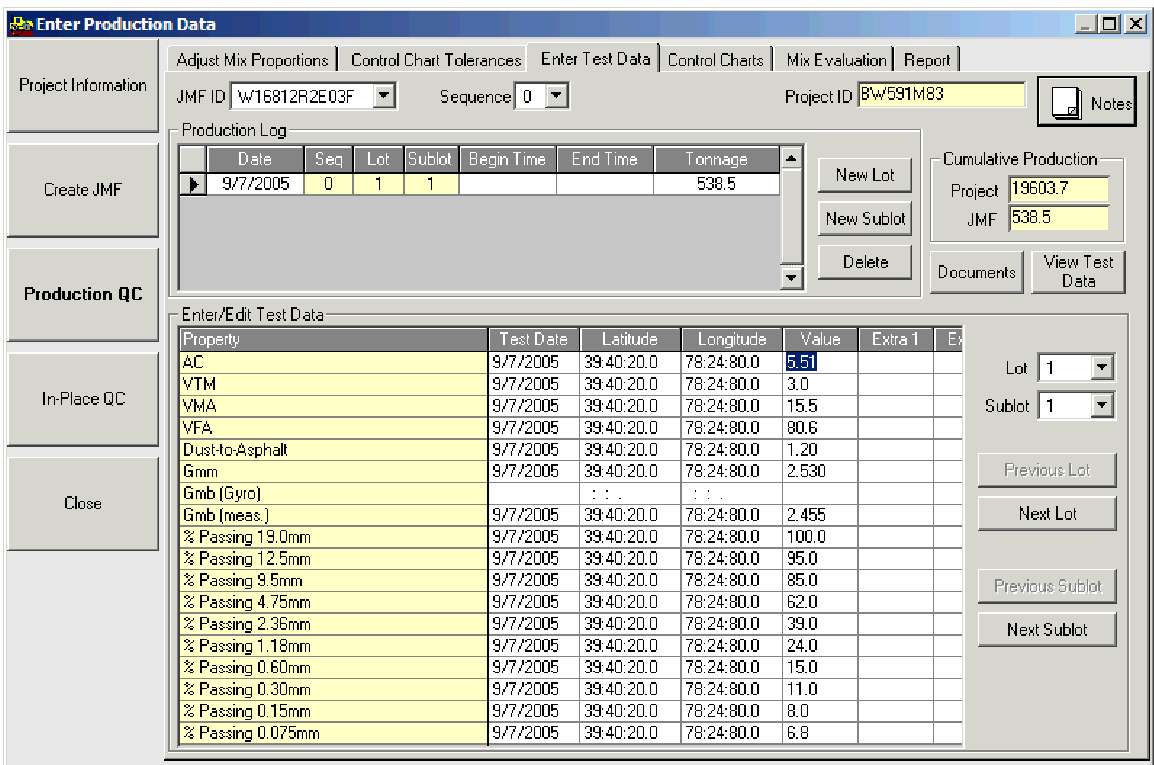

Figure 22. Test data entry screen from MarylandWare QC/QA software.

Task 4: Prepare Project Report and Technology Transfer

The findings from Tasks 1 through 3 will be synthesized to: (a) evaluate the success of the concept; and (b) if judged a success, make recommendations for the next steps in the development and implementation of the concept as a practical production technology.

Communication of the results from this concept exploration study is vital to any eventual commercialization and widespread usage of the technology. Planned components of the communication program include the following:

- Final project report to FHWA (as well as interim reports as required). This final report will document all activities, findings, and recommendations from the project.
- Presentation of preliminary findings to TRB committees AFD10 Pavement Management Systems and/or AFK50 Characteristics of Bituminous Materials to Meet Structural Requirements at the TRB Annual Meetings in Washington in January 2008. Dr. Schwartz, the Principal Investigator, is a member of AFK50 and Mr. Peter Stephanos, the former MDSHA Director of the Office of Materials and Technology, is a member of AFD10. Consequently, there should not be any problems in adding these presentations to the committee agendas.
- Presentation of preliminary findings to the ASCE Transportation and Development Institute's Highway Pavements committee. Dr. Schwartz is a member of this committee.
- Presentation of final project results at the TRB annual meeting in January 2009, with subsequent publication in the *Transportation Research Record*. Alternatively/additionally, the results may be presented/published at the AAPT meetings in the spring of 2009.[2]
- Briefings for the National Asphalt Paving Association (NAPA is conveniently located in Lanham, MD) and regional industry organizations such as the North East Asphalt User Producer Group.
- Preparation of an article for publication in the FHWA *Focus* newsletter.
- Publication of findings on the FHWA and the UMD Pavement Engineering web sites.
- If requested and based upon the promise shown by the technology, presentations to the AASHTO Subcommittee on Materials and the AASHTO Subcommittee on Construction.

The resources of the UMD Transportation Technology Transfer Center (MD T^2 Center -- http://www.ence.umd.edu/mdt2center/) will also be employed as appropriate. The MD T^2 Center provides ready access to the network of Local Transportation Assistance Program offices across the U.S.

Assuming success in the concept evaluation stage (the subject of the present proposal), the next step in product transfer and implementation would be to refine the design of an integrated RFID tag/GPS system for production usage. This would be followed by larger scale field trials under a wide range of condition and aggressive publicizing/promotion within the paving industry. The

[2] The field evaluations will not be complete in time for the August 1 paper deadline for the January 2008 TRB Annual Meetings or the Spring 2008 AAPT conference.

prospects for the eventual commercialization of the technology are quite favorable. The system is based upon existing technology, with many vendors already marketing RFID for other types of supply chain control applications. The large quantity of tags that would be consumed in production paving by even just a subset of the paving industry should make this an attractive commercial product, either as an additional product line for existing RFID manufacturers or to a new start-up venture (e.g., through the Maryland Technology Enterprise Institute—see http://www.mtech.umd.edu/). Commercialization, including patent protection as appropriate, can and will be energetically pursued once the concept is proven successful.

Phase II Schedule

Figure 23 summarizes the proposed schedule for Phase II. It is based on an assumed start date of July 1, 2007. This reflects a one month overrun in Phase I required to finalize the report and to obtain approval to proceed for Phase II. The project schedule is designed to permit field trials to be conducted during the 2007 paving season. Phase II duration is still scheduled at 7 months as originally proposed, but the completion date has been pushed back one month to January 31, 2008.

Several key milestones for Phase II are identified in Figure 23:

(a) Project kick-off meeting with FHWA technical representatives at the commencement of the contract. (Phase I milestone)

(b) Quarterly progress report

(c) Quarterly progress report

(d) Phase I final report. Progress meeting with FHWA technical representatives to present and discuss the Phase I findings. (Phase I milestone)

(e) Quarterly progress report

(f) Quarterly progress report. Presentations to TRB and ASCE technical committees during the TRB Annual Meetings.

(g) Phase II final report. Final project meeting with FHWA technical representatives to present and discuss the project findings.

(h) (Not shown on Figure 23) Presentation of project findings in formal papers at the January 2009 TRB Annual Meetings and/or the Spring 2009 AAPT conference.

All status reports will include the following:

- A clear and complete account of the work performed during the reporting period
- An outline of the work to be accomplished during the next reporting period
- A description of any problems encountered or anticipated that will effect the completion of any individual task or task order with the time and cost constraints, as well as recommended solutions to the problems. If no problems are encountered, this is to be reported as well.
- A tabulation of the planned, actual, and cumulative person-hours expended by person by task/task order.
- A chart showing current and cumulative expenditures versus planned expenditures, including labor, travel, and material expenses incurred during the reporting period.

Month	9/06	10	11	12	1/07	2	3	4	5	6	7	8	9	10	11	12	1/08
Month from Start	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Phase I																	
Task 1: Identify Feasible RFID Devices for HMA																	
1.1: Literature Review																	
1.2: Identification of RFID Technology																	
1.3: Prototype Tag Development																	
Task 2: Identify Candidate Projects																	
Phase II																	
Task 3: Carry Out Phase I Plan																	
Task 4: Project Report/Technology Transfer																	
Milestones	(a)		(b)			(c)			(d)				(e)			(f)	(g)

Figure 23. Proposed project schedule for Phase II.

Phase II Budget

Phase I was completed within the original proposed budget. The budget for Phase II will remain as originally proposed. For completeness, the proposal budget for Phases I and II is included as Table 6. The total budget proposed for Phase II is $50,155.

Table 6. Project budget (from original proposal).

			Phase 1				Phase 3				Total		
Name	Role in Study	Hourly Rate[1,2]	Hours[1]		%Time[3]	Cost	Hours[1]		%Time[3]	Cost	Hours	%Time[3]	Cost
Direct Salary			Task 1	Task 2			Task 3	Task 4					
Charles W. Schwartz	PI	$65.10	192	24	15.0%	$14,062	84	84	15.0%	$10,937	384	15.0%	$24,998
(Graduate Student TBD)	Grad Res Asst	$23.28	620	100	100.0%	$16,762	280	160	100.0%	$10,243	1160	100.0%	$27,005
Fringe Benefits													
Charles W. Schwartz	PI	$9.77				$2,110				$1,641			$3,752
(Graduate Student TBD)	Grad Res Asst	$10.34				$7,445				$4,550			$11,994
Task Labor Hours			*812*	*124*			*364*	*244*			*1544*		
Task Labor Costs			*$35,219*	*$5,159*		*$40,378*	*$15,703*	*$11,668*		*$27,371*			*$67,749*
Other Direct Costs													
GRA Tuition Remission						$6,174				$3,704			$9,878
RFID equipment and expendable supplies						$5,000				$1,000			$6,000
Miscellaneous UMD technical experts						$5,000				$0			$5,000
Travel										$1,300			$1,300
Long distance telephone						$225				$90			$315
Publications and other references						$250				$0			$250
Report preparation						$250				$500			$750
Department IT support						$1,718				$1,019			$2,737
Total Other Direct Costs						*$18,617*				*$7,613*			$26,231
Total Direct Costs						*$58,996*				*$34,984*			*$93,980*
Indirect Costs (48.5% MTDC)						*$25,618*				*$15,171*			*$40,789*
Total Cost						**$84,614**				**$50,155**			**$134,769**

Notes:

1. The University of Maryland accounting system tracks labor on a percent-of-effort basis by academic/summer semester. Hourly rates and hours of effort are estimates only.
2. Hourly rates include direct salary plus fringe benefits.
3. Assumes 9 month duration for Phase 1 and 7 month duration for Phase 2. Assumes 1920 hours per year (1160 hours per year for Graduate Research Assistant).

APPENDIX A: ANNOTATED BIBLIOGRAPHY

Anonymous (2002). "Tracking Concrete Cubes for QA," *RFID Journal*, August 18, http://www.rfidjournal.com/article/articleview/194.

RFID tags embedded in concrete test cubes were evaluated as an alternative to manual tracking in order to reduce human errors and costs for tracking quality acceptance (QA) test data. This "Cube Info" application employed passive 13.56 MHz tags with 228 bytes of storage. The tags were approximately the size of a quarter and were encapsulated in a hard plastic protective casing. A handheld reader/writer was employed to scan the cubes at the job site and encode them with field information. A fixed reader/writer attached to the laboratory weigh scales and compression test machines were used to record QA test results. Read range is not reported in the article, but from the accompanying figures it appears to be on the order of 1 meter.

Concrete mix information for an individual mixer truck is entered into the handheld reader/writer via a barcode attached to the paper load slip. After a slump test has been performed at the sight, the encapsulated active RFID tag is place inside the freshly prepared 6" x 6" test cube. The handheld reader/writer the writes the mix information, slump test results, and date to the active RFID tag. The cube is then sent to laboratory for curing. After curing, it is weighed and the weight data is transferred from the weight machine RFID reader/writer to the tag embedded in the cube. A compression test is finally performed, and these results are also transferred by the associated RFID reader/writer to the tag. The protective plastic casing enables the RFID tag to be retrieved intact after the test for download of the complete data set. The encapsulated tags can be reused (over 20 times). After verification of the test results, they are posted to a materials database and/or sent via email to the concrete producer and others.

The pilot implementation of the Cube Info system was reported as giving good results. No major technical problems were reported. Nonetheless, acceptance of this system does not appear to be speedy or widespread.

AXCESS, Inc. (2006). "AXCESS' Active RFID Solution Utilized by Bechtel to Automate HAZMAT Truck Payload Management," press release, May 9, http://www.axcessinc.com/press/050509bechtel.doc.

In this application, RFID is used to monitor environmentally hazardous material movement with minimum hindrance in its transport. Active RFID tags are installed on trucks and drums. When the truck passes a weigh station its load, contents, and other information is scanned and automatically uploaded to a data base.

Collins, J. (2004). "Case Builds for RFID in Construction," ***RFID Journal*****, January 5, http://www.rfidjournal.com/article/articleview/720/1/4/.**

RFID technology was evaluated as an alternative to bar coding for tracking the shipment and delivery of metal pipes from a fabrication plant in Texas to a construction site. The RFID system consisted of active UHF (915 MHz) RFID tags from Identec and Phase IV Engineering, an Identec handheld reader connected to an iPaq PDA, and a CargoWatch stationary reader. Read-write range in non-interfering environments was approximately 100 meters. Only tag identification information was evaluated.

The focus of the study was to determine whether reliable readings could be obtained when the RFID tags are placed on a pipe surrounded by a large number of other pipes on the back of the truck. The tags were mounted on the pipes after loading onto the truck to avoid damage by the loading process. Two read modes were evaluated. Stationary loaded trucks were scanned by a worker with the handheld reader who moved around the truck trailer. Moving trucks were scanned as they were driven past a stationary reader location.

Tag reads for stationary trucks were 100 percent accurate up to a range of 10ft. Accuracy dropped slighly for a moving truck passing the stationary reader. However, it rebounded to 100% when the truck stopped briefly near the stationary reader.

Ergin, E., and Hendrickson, C.T. (2007). "Utilization of Radio-Frequency Identification Tags for Transportation Infrastructure Management: Tracking Engineered-to-Order Elements and Materials Throughout Their Life-Cycles," ***Transportation Research Board 86th Annual Meeting*****, Washington, DC, January, Paper No. 07-2788.**

Information flow related to materials and components used in transportation infrastructure systems and their supply chains are plagued with inefficiencies caused by inadequate or late deliveries and installation of components at wrong locations. This paper provides of vision of how RFID tags can be used as a means to track components from long distances, store information on these components, and allow multiple parties to access this information. A requirements analysis and a limited set of field tests were performed to explore the technical feasibility of using RFID technology for these purposes. The experiments demonstrated that it is technically feasible to add intelligence to the components in transportation infrastructure systems in order to collect status information automatically within the supply chain.

Goodrum, P.M., McLaren, M.A., and Durfee, A. (2006). "The Application of Active Radio Frequency Identification Technology for Tool Tracking on Construction Job Sites," ***Automation in Construction*****, Vol. 15, pp. 292-302.**

The objective of this study was to improve the tracking of hand held power tools on construction sites to make them more easily available to a worker when needed. Commonly used tools (corded hammer drill, portable band saw, reciprocating saw) at three construction projects were identified and tagged. Active UHF (915 MHz) RFID tags with lithium/thionyl chloride ($Li/SOCl_2$) and 32

Kb of memory were employed. The tags, approximately 1" x 5" in size, were mounted internally within the plastic tool housings. A handheld reader connected to a PDA was used to collect data.

Contractors were allowed to move tools freely according to their needs. Readings were taken every week at the job sites. Readings were taken while the tools were stored in top-opening metal gang (tool storage) boxes with the lid open. Reading distance and direction from the tools in the gang box were noted. Evaluation included read range, integrity of stored inventory and maintenance data on the tag, and ability of reader to update that data.

Reads in environmentally controlled laboratory conditions were successful up to ranges between 15 to 25 meters. This dropped in the field to between 3 to 9 meter. The variation in the field read ranges was attributed to temperature influences and metal interference. The electromagnetic field produced by the tool itself did not affect the RFID signal. It was also noted that the active RFID could be short-circuited when drenched in water.

The largest read range decrease occurred at one site where temperatures fell to -12^{o}C. Battery performance in the active RFID tag is adversely affected by these low temperatures.

International Road Dynamics, Inc. (2004). "Wireless Concrete Maturity Meter," news release, May, http://www.identecsolutions.com/fileadmin/user_upload/PDFs/case_studies/News_Release_ird_-_Wireless_Concrete_Maturity_MonitorV2_Eng.pdf.

Concrete maturity time is predicted using measured temperatures from an embedded RFID sensor and as input to predictive techniques like the Equivalent Age (Arrhenius) and/or Nurse-Saul models. The RFID technology for this application consists of an Identec iQ active UHF tag and a handheld reader. The system can read tags up to 8 inches inside concrete. This system in conjunction with the predictive models gives estimates of the compressive strength of concrete on site. This is more accurate than laboratory techniques which do not share the same environmental and other conditions (e.g., volume) as on site.

Johns Hopkins University Applied Physics Laboratory (2005). "New Sensors Promise to Drive Down Highway Maintenance Costs," news release, January, http://www.jhuapl.edu/newscenter/aplnews/2002/highway.asp.

In this study, an RFID tag is combined with a conductivity sensor to monitor the corrosive environment in reinforced concrete bridge decks. The "Smart Aggregate" is a passive RFID tag roughly the size of a quarter that is encapsulated in a high compressive strength ceramic. During preliminary field trials, the Smart Aggregate tags were embedded in the concrete bridge deck for the Johns Hopkins/Gorman Road bridge over US Route 29 in Maryland. Results of these trials have not been located as of the time of this writing.

Jaselskis, E.J., Anderson, M.R., Jahren, C.T., Rodriguez, Y., and Njos, S. (1995). "Radio-Frequency Identification Applications in Construction Industry," ***Journal of Construction Engineering and Management*****, ASCE, Vol. 121, No. 2, June, pp. 189-196.**

This early paper on RFID applications in construction engineering begins with a basic description of the various technology options available and their respective advantages and limitations. Current and potential applications of this technology are then described. Although many of these applications are speculative, they suggest a broad impact of RFID technology in the construction industry.

Jaselskis, E.J., and El-Misalami, T. (2003). "Implementing Radio Frequency Identification in the Construction Process," ***Journal of Construction Engineering and Management*****, Vol. 129, No. 6, November/December, pp. 680-688. (see also Jaselskis, E.J., and El-Misalami, T. (2003). "RFID's Role in a Fully Integrated, Automated Project Process,"** ***Construction Research Congress in Construction: Wind of Change: Integration and Automation*****, ASCE.)**

This paper is in essence an update of Jaselskis *et al.* (1995). The basic concepts and advantages and limitations of available RFID technologies are described. Key outcomes from a construction industry-RFID supplier workshop held to disseminate information and generate suitable application ideas in construction are summarized. This workshop generated one pilot application that was conducted to demonstrate the applicability of RFID to the material procurement process at a construction site. The pilot tests showed that RFID tags reduced the time required to download data into a company's material tracking system and reduced the potential for duplicate data entries. The application demonstrated the benefits of the technology in the materials receiving process.

Jaselskis, E.J., Grigas, J., and Brilingas, A. (2003). "Dielectric Properties of Asphalt Pavement," ***Journal of Materials in Civil Engineering*****, ASCE, Vol. 15, No. 5, September/October, pp. 427-434.**

Electromagnetic wave absorption, reflection, and transmission through asphalt concrete depend on the dielectric properties of the material. Asphalt concrete samples of different densities were studied in the frequency range from 100 Hz to 12 GHz to determine the temperature and frequency dependencies of the real and imaginary permittivity components. The principal findings were: (a) permittivity and loss depend on frequency and temperature; (b) permittivity increases with increasing pavement density; (c) permittivity slightly increases with temperature; (d) moisture strongly increases permittivity and loss at low frequencies and only slightly at high frequencies; and (e) the penetration depth of electromagnetic waves in asphalt pavements is about 12–14 cm at 8 GHz and only about 4 cm at 30 GHz. Although the focus of this study was on microwave transmission (frequencies between about 1 GHz and 300 GHz) to determine the density of in-place asphalt concrete, the data and results are also relevant to ground penetrating radar (GPR; frequencies between about 100 MHz and 1.6 GHz) and UHF RFID (frequency of approximately 900 MHz).

Naresh, A.L., and Jahren, C.T. (1997). "Communication and Tracking for Construction Vehicles," *Journal of Construction Engineering and Management*, ASCE, Vol. 123, No. 3, September, pp. 261-268.

This survey article describes the potential efficiency benefits of advanced communication and tracking systems (ACTS) for construction vehicle fleets such as dump trucks, concrete trucks, low boy trailers, and scrapers. Three advanced systems are covered: signaling systems, continuous communication and tracking systems, and radio frequency identification. Implementation and potential value of these systems for construction fleet management are described in conceptual terms only.

O'Connor, M.C. (2006). "RFID Cures Concrete", *RFID Journal*, October 30, http://www.rfidjournal.com/article/articleview/2673.

The time taken for concrete to mature depends on volume and temperature. As a consequence, test cylinders overestimate maturity time. The objective of this study was thus to measure the actual concrete maturity time on site by employing temperature sensing RFID technology.

The RFID technology employed in this application was an Identec iQ 915 MHz UHF active tag with an integrated temperature sensor. The RFID tag is placed in the wet concrete during construction. The temperature readings of concrete are transmitted to the handheld reader, which downloads the information to a hand held computer capable of running concrete maturity time algorithms that model the relationship of maturity to temperature during curing. The RFID temperature sensor tag found that the required concrete strength at the actual site is achieved in only 1/3 of the time predicted by cylinder tests. This can significantly shorten the construction time for a building.

Peyret, F., and Tasky, R. (2004). "A Traceability System between Plant and Work Site for Asphalt Pavements," *Computer-Aided Civil and Infrastructure Engineering*, Vol. 19, pp. 54-63.

This study, conducted as part of the European OSYRIS (Open System for Road Information Support) project, evaluated the linkage of RFID and GPS technologies for associating asphalt mix data collected at the production plant with location of the material on the roadway. Of all of the material reviewed from the literature, this is the most relevant to the present project.

In this prototype system (see Figure 24), the mix properties of a batch are stored in the plant computer. When a loaded transport truck fitted with an RFID tag leaves the plant, the plant computer transfers the mix properties, temperature, and weight of the load via the reader to the active RFID tag on the truck body. The paver at the job site is equipped with an RFID reader, GPS transponder, and a computer (Figure 25). When the transport truck arrives at the job site and unloads into the paver, the paver instrumentation reads the tag ID and other information and combines this with GPS coordinates to record the starting and ending times and latitude/longitude coordinates along the roadway for that specific load

The RFID technology employed in this application consisted of an active UHF (866 MHz) RFID tag having an approximate size of 0.15 x 0.03 x 0.02 meters. Reported read ranges were 15 m effective and 30 m nominal. The 0.4 x 0.25 x 0.3 plant and paver antennas had coverage angles of approximately 120 degrees. An OMNISTAR Differential GPS mounted on the paver was used to determine latitude, longitude, and time data.

During the prototype implementation, some minor information was lost from the tags, but this was judged to have no significant impact on the test results as such losses were anticipated in the prototype. There were some occasional difficulties getting an accurate GPS reading when the satellite signal was obstructed. The software for the prototype system was not fully integrated and therefore the data reading and recording processes were not fully automated. This was to be remedied in future phases of the project. However, it is unclear whether these future phases were ever conducted. The authors have been contacted via email to see if any additional work on the system has been completed, but no reply has been received at the time of this writing.

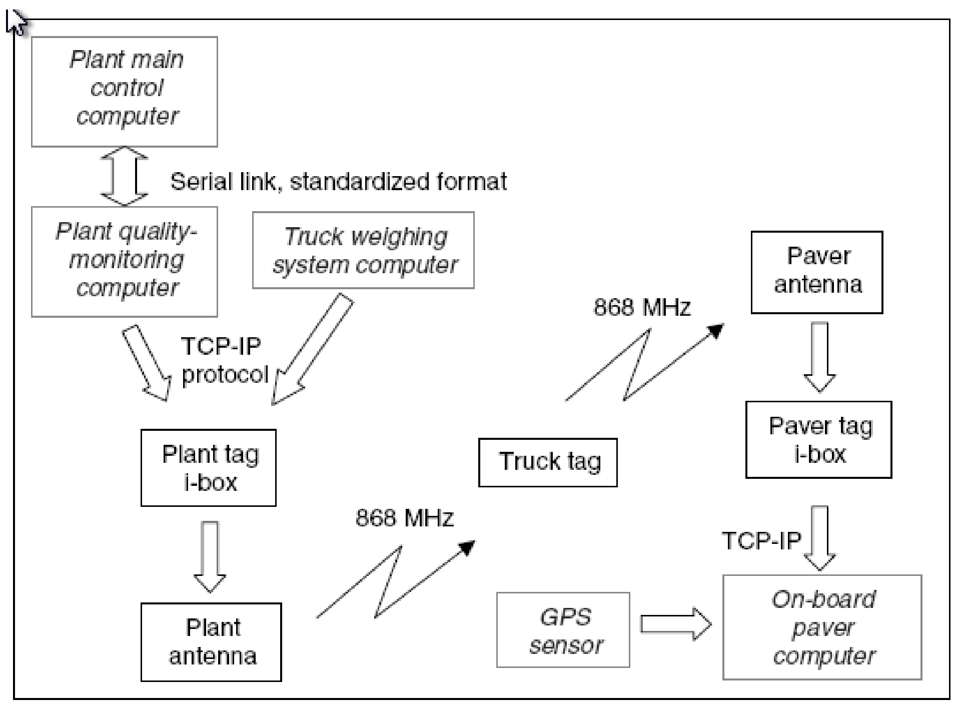

Figure 24. System schematic for prototype asphalt material tracking system (Peyret and Tasky, 2004).

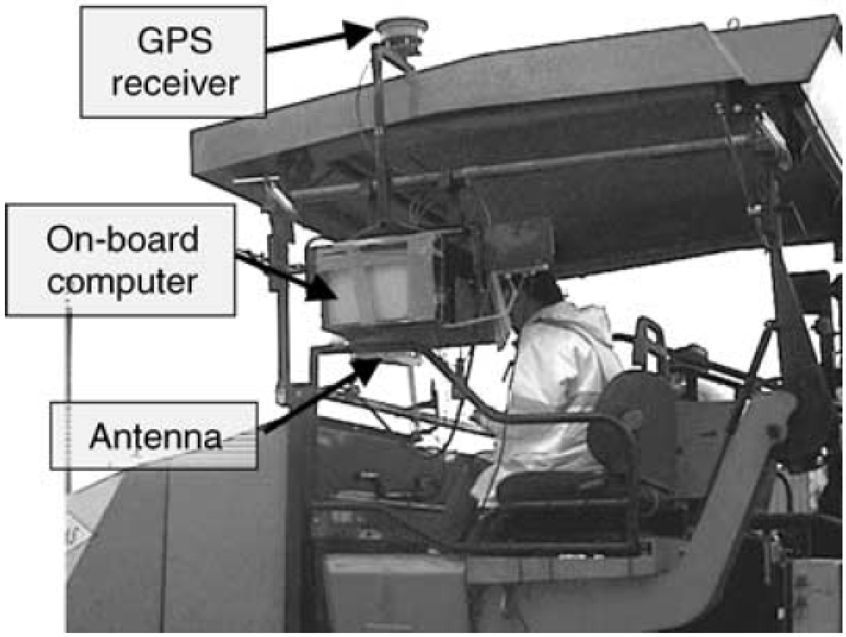

Figure 25. Onboard paver instrumentation for prototype asphalt material tracking system (Peyret and Tasky, 2004).

Sawyer, T. (2004). "Researchers are Getting Serious About Electronic Tracking Tags," ***Engineering News Record*****, Vol. 253, No. 23, December 13, pp. 28-29.**

This article describes how large construction firms have been employing RFID technology for a variety of applications, including automatic inventory control, automated tool check-out, and tracking of construction components in storage yards.

Song, J., Haas, C.T., and Caldas, C.H. (2006). "Tracking the Location of Materials on Construction Job Sites," ***Journal of Construction Engineering and Management*****, ASCE, Vol. 132, No. 9, September, pp. 911-918. (see also Song, J., Haas, C.T., Caldas, C.H., and Liapi, K. (2005). "Locating Materials on Construction Site Using Proximity Techniques,"** ***Construction Research Congress 2005: Broadening Perspectives*****, ASCE.)**

This paper presents an approach by which construction materials can be tagged and then automatically identified and tracked on construction sites without interfering with regular site operations. A construction supervisor equipped with a portable RFID reader and a GPS transponder roves the site. A combination of proximity of reads from discrete ranges allows the construction material item to be located within a two dimensional grid overlaying the construction site. Off-the-shelf RFID passive technology was employed in this study, but specifics are not provided regarding operating frequency, or other parameters.

Stone, W.C., Pfeffer, L., and Furlani, K. (2000). "Automated Part Tracking on the Construction Job Site," ***Robotics 2000,*** **ASCE Conference on Robotics for Challenging Environments, Albuquerque, NM, March. (available at http://fire.nist.gov/bfrlpubs/build00/PDF/b00003.pdf).**

This system design exercise was conducted as part of a National Institute of Standards and Technology (NIST) initiative to develop web-based techniques for tracking prefabricated components on construction site in real-time. The basic concept is that each component to be shipped to a site is identified with a unique bar code or RFID tag. The bar code/RFID tag is scanned and the identification information downloaded to a laptop when the component arrives on the job site. The component ID is then sent from laptop to the project database, where it is joined with the whole description of the component, e.g., from the manufacturer's specification book. The site inspector also enters the 3D coordinates of the component's on site storage location using a 3D coordinate measuring tool. The component is tracked by sensors that automatically update the project data base. The project data base information can be sent via the web to a distant project management office, were all activity can be viewed in real time in 3D space.

A pilot test monitored site activity from an office located approximately 1 km away from the job site. However, only barcodes were used in the pilot. Although not implemented, the author anticipated much better performance using RFID technology.

Swedberg, C. (2006). "RFID Markers Track Buried Cables at Atlanta Airport," ***RFID Journal*****, September 12, http://www.rfidjournal.com/article/articleview/2647/.**

This application is focused on locating underground cables and pipes at the Atlanta airport using RFID. Ball markers containing RFID tags were used to store identification, location, and other information for each utility cable and pipe. Different categories of utility cables and pipes were assigned different RFID tag frequencies. Passive RFID tags with 256 bits of memory and operating frequencies ranging from 66 to 169 MHz were employed for this application. The system is reported to work well, with tags readable up to five feet underground.

Violino, B. (2007). "RFID Rocks at Graniterock," ***RFID Journal*****, January 22, http://www.rfidjournal.com/article/articleview/2905/1/4/.**

RFID technology was employed to improve efficiency of movement of trucks at Graniterock quarries. The system was based on a TransCore IP Ltd. passive RFID tag (approximate dimensions of 2" x 12") scanned using a fixed location TransCore reader. A key focus of this implementation was integration of the RFID data with other Graniterock business operation software and databases.

The quarry operations staff is informed via telephone about the RFID tag identification, trucking company name, and other information as the truck approaches the entrance. This information is fed in to operations data base. As the truck enters the quarry weigh station, the fixed reader reads the tag ID and combines this with the empty truck weight and other information that is correlated with the pre-arrival information already stored in the database. As the loaded truck leaves, it again passes the reader, the tag ID is again read, and the corresponding loaded weight is automatically uploaded to the data base. A hardcopy receipt/billing slip is printed for the truck operator.

Although the details of the reader configuration and read range are not stated, the test trials of the system were reported as very successful. There was an initial problem distinguishing incoming and outgoing trucks passing the fixed reader simultaneously, but this was resolved via modification of the direction and power of reader. Overall, Graniterock found that the sutomated RFID system dramatically reduced human input (i.e., staff time) and produced significant time savings.

Wasserman, E. "Construction's Building Blocks: RFID," *RFID Journal*, http://www.rfidjournal.com/magazine/article/2922/1/394/.

A nontechnical survey article describing several applications of RFID technologies to the construction industry.

Wessel, R. (2006). "RFID Chops Timber Costs," *RFID Journal*, April 3, http://www.rfidjournal.com/article/articleview/2220/1/4/.

RFID technology was integrated into a Log Tracking System to minimize logs lost in the forest and to improve the efficiency of timber log deliveries to sawmills. An RFID tag encased in a plastic nail is hammered into the base of a freshly cut log in the forest. The RFID identification number is scanned and downloaded to a handheld computer where it is combined with other manually-entered characteristics of the log. These data are transmitted wirelessly to a central main data base. After the trees have been transported from the forest to the road side, the tag is again scanned and the identification number transmitted to the main data base. The main data base compares the ID numbers of the cut logs from the forest against the ID numbers of the logs along the road side to reduce the chances of leaving a log in the forest. The ID numbers of logs are again scanned at time of loading into the haul trucks and when delivered to the sawmill.

The RFID technology employed in this application consisted of a passive 125 KHz tag encased in a special plastic nail. The plastic nail is made of polyamide reinforced with glass fiber and is approximately 0.2" in diameter by 1.4" long. A special hammer is used to drive the RFID nail. The handheld reader is attached to a wristband and is connected to a handheld computer. Maximum read range was 1.2"; this sounds marginal, but the nails are clearly visible in the ends of the logs at all steps and can therefore be easily located and read at close range. Other data regarding the log are entered into the handheld computer using a voice input system via a microphone attached to the logger's helmet. Data are transmitted wirelessly from the handheld computer using a WLAN connection or the GSM network.

The pilot implementation of this system was successful. No trunks were lost by using RFID. The LTS worked in rain and snow conditions. The RFID tags did have a small read range and store only an identification number, but any enhancements would make the tags economically infeasible. One problem encountered early on was damage to the nails when they were hammered into the log, particularly if the log was frozen. A special hammer was developed to solve this problem.